Utility Service to Electrified Railroads

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During the past decade American railroads have expressed considerable interest in electrification, but no major electrification commitments have been made except for the extensions in the Northeast Corridor.

It is assumed that a railroad operation of significant size will be served at 60 Hz and probably either 25 or 50 kV. The economic advantages and proven performance of the 25 to 50-kV commercial-frequency power-delivery system appear to favor this type of service for future electrified operations. This assumption is supported by a number of North American and foreign technical and economic studies.

When the supplying utility develops a service proposal for prospective railway service, it must consider the electrical characteristics of the railroad load; the effects of the new load on the utility's facilities; the effects of the load on other customers of the utility; the direct and indirect costs and investments required to serve the railway; and the regulatory, rate, contractual, and billing considerations involved in meeting the railroads' service requirements. The electric railroad load has several service characteristics that are unique in regard to cost of service and technical aspects. The service agreement with the railroad must recognize and resolve the economic and service aspects of the railroad's electrical needs in a manner that is acceptable to the railroad, the supplying utility, and the interested regulatory agencies.

IMPACT ON THE UTILITY SYSTEM

The railroad's power demands affect the utility system's phase balance and voltage, voltage dips, possible parallel tie with utility facilities under certain service conditions, feedback harmonics, and ground return effects. The reduction of the electrical effects to technically acceptable levels may in many cases involve substantial investments on the part of the utility system or changes in the location or characteristics of the electrical service facility.

Phase Unbalance

The single-phase railroad load, which is never perfectly balanced because of train diversity, imposes an unbalanced load on the utility system, particularly on the line or lines from which the single-phase load is fed. This unbalanced loading creates negative phase-sequence currents, which have a more serious effect on generating equipment than on any other utility apparatus. The amount of negative phase-sequence load that a generator is capable of carrying is principally a function of the heating of the slot wedges and rotor body ends. Depending on their design and the length of time they are subjected to an unbalanced load, generators can absorb varying amounts of negative phase-sequence currents. American equipment manufacturers have published data indicating that, operating at rated voltage and rated load, generators are capable of carrying a 5 percent negative phase-sequence current continuously. British and Japanese design permits up to a 10 percent negative phase-sequence current, although in neither country has the amount of unbalanced loading resulting from railway electrification exceeded 5 percent.

Since the power demand from the railroad would be connected to the overall transmission system, the negative phase-sequence currents would affect different generators in different amounts; those electrically closest to the supply points would be subjected to the larger amount of unbalance. Computer programs are available to translate train movements into power demand in kilowatts. Their use can permit the design of an electrification system that can keep the phase unbalance from exceeding the allowable limit by proper sectionalizing and selecting the correct transformer size.

The computer can be programmed to read out the railroad's power demand by substation locations and by selected time intervals, both for normal railroad operation and for abnormal operations, such as after derailments. Thus, the maximum demand, maximum unbalance, and the time of either or both can be determined. These may or may not normally occur simultaneously and may or may not coincide with the peak load for the utility system. To determine whether the phase unbalance exceeds the limits, the railroad load pattern must be compared with generating schedules at all times of the day.

Voltage Unbalance

The single-phase railroad load can cause voltage unbalance between phases that can overload or damage three-phase equipment that belongs to other customers or the utility. The unbalanced voltage is most troublesome to polyphase motors, in which it can cause overheating. Although the standards of the National Electrical Manufacturers Association give no permissible limit for unbalance, a 5 percent unbalance is generally recognized as the tolerable maximum. Foreign practice has been to limit this unbalance to 3 percent, except in France, where higher limits (in some cases as great as 7 percent) have been allowed in rural areas. From a technical viewpoint, the primary effect of the unbalanced voltage appears to be the probable, but unproven, loss of life to the customers' motor insulation.

Voltage Dips

The sudden impact on electric demand posed by a heavy train can cause an objectionable dip in voltage levels on the supplying utility system. This objectionable dip generally occurs when the train crosses a phase break. The problem has been encountered in Japan and France, but in most cases the system's short-circuit capacity that is required to correct for the effects of phase and voltage unbalance will also correct for sudden dips.

Phase Breaks and Parallel Operation

To limit the effects of phase unbalance a utility will generally place adjacent railroad substations on different phases. This method of service, known as the center-feed system, has the advantages of providing the best distribution of the railroad load between phases and of avoiding the establishment of a single-phase tie between two points on the utility system. A phase break is generally established midway between the supply substations,
Although it is very desirable from the viewpoint of the utility, the center-feed system presents a major disadvantage for train operations when the phase break between substations occurs on a major grade. When freight locomotives are working at maximum output, e.g., on a steep grade, the loss of power to each locomotive unit as it crosses the phase break would create momentary changes in tractive effort that would produce objectionable slack actions in the long freight trains.

These momentary changes in power would inevitably cause trains to break in two. Therefore, if a grade is too long to be supplied from a single substation, it may be necessary to operate two or more adjacent supply points in parallel that are served from the same phase, despite the problems presented to the utility system. The French National Railways operates several stations in parallel as standard practice, and this apparently has not caused significant power-system problems. The principal advantages to the railroad's power-delivery or catenary system of tying adjacent supply substations together with a transformer at each end are that

1. Current loadings on the catenary system are reduced, thereby decreasing the chances of voltage drops and system losses;
2. In case of a transformer or transmission-line outage, supply continuity is assured, whereas under the center-feed system there is a short dead period while the associated automatic transfer switching is taking place; and
3. The objectionable effects of phase breaks are moved to a location where the voltage is at its maximum strength rather than at its weakest.

Many of the objections to the establishment of a parallel point-to-point tie with the utility system can be eliminated if proper relaying and fault-sensing equipment is installed.

Harmonics

The harmonics generated by locomotives with silicon-controlled rectifiers, although they present notable problems to railroad signal systems, are as a general rule effectively reduced by the natural system capacitance to a point at which they do not affect the facilities of the utility. French and British experience has confirmed that harmonic effects are minor in nature and that they have not affected the apparatus of the utility or of other customers.

CHARACTERISTICS OF RAILROAD POWER DEMAND

At today's traffic levels, the electrified railroad's power demand presents potential national energy requirements of 72 to 108 PJ (20 to 30 billion kW-h). At the level of 27 Tg (30 million gross tons) annually that is generally considered sufficient to justify electrification, annual energy requirements of 1.75 to 2.25 TJ/km (800 000 to 1 000 000 kW-h/mile) may be anticipated.

Assuming the approximately 32 000 km (20 000 miles) that today carry about 60 percent of the nation's rail traffic undergo electrification, the railways will create an annual demand for about 72 PJ (20 billion kW-h), with a peak national demand of about 3000 MW. Traffic growth could increase this market to more than 108 PJ (30 billion kW-h) on the same 32 000 km of track. In the nation as a whole, the demand imposed by railroad electrification will probably be less than 1 percent of the national peak demand.

The demand of a typical 800-km (500-mile) railroad in the country with occasional short gradients of 0.5 percent or less is estimated to be from 80 to 120 MW for a single-track line and from 140 to 180 MW for double-track lines. Main-line grades of more than 1 percent may result in demands as great as 100 MW in an electrified zone of less than 160 km (100 miles). In planning the electrification of operations with grades, care must be taken to coordinate the amount a train is hauling and the operating schedules with the general demand on the electric system.

Typical railroad load factors improve as the length of track electrified increases and, therefore, as the number of supply points increases. An 800-km electrification project might be served from 15 to 30 delivery points, depending on the voltage of the catenary and the operating conditions. Load factors on lines that have sufficient traffic density to justify electrification have varied from 55 percent to more than 70 percent for a 650 to 1000-km (400 to 600-mile) double-track route. The power factor for railroads served by several delivery points will be a lagging factor of 0.85 to 0.90.

The impedance of the catenary system will, in most cases, limit the supply capability of 25-kV catenary system stations to 25 to 35 MW and of 50-kV stations to 40 to 50 MW. Power factors may be as low as 0.65 to 0.70, under the most adverse starting conditions, with only one train in the service section, to as high as 85 to 90 percent. In recent studies, the load factor of individual stations has been found to range from 10 percent to slightly more than 40 percent.

Railroad officials indicate that there will probably be two or three 6-MW (8000-hp) locomotives per train. On level track, each 6-MW locomotive would be capable of moving about 2 Gg (2450 tons) at 130 km/h (80 mph) or 3.5 Gg (3800 tons) at 105 km/h (65 mph). Maximum train demands of 25 to 30 MV-A may occur when 7 to 9 Gg (8000 to 10 000-ton) freight trains are operated at speeds of 110 km/h (70 mph) and more. The average use of energy by a train depends on speed, frequency of speed changes or stops, acceleration rates, and the grade. Recent studies indicate that the average requirement is 60 to 75 kJ/Mg-km (25 to 30 kW-h/1000 tons-miles).

The electric locomotive that is expected to provide power in the 1970s and 1980s will be a six-axle, six-motor locomotive that has a solid-state rectifier and is to 9 MW of power (8000 to 12 000 hp). The locomotive will present a power demand at the pantograph that is about 20 percent greater than its rail power and a capacity demand of 8 to 12 MV-A. The modern locomotive with a solid-state rectifier operates at a lagging power factor that varies from less than 10 percent standing still to 85 to 90 percent at maximum power output.

RAILROAD SERVICE REQUIREMENTS

The service requirements of railroads with respect to service reliability and regulation of voltage are comparable to the requirements of most industrial customers. Railroads can generally tolerate power interruptions of short duration (up to 60 s); this will permit motor-operated air-break switches to operate without adverse effects. Therefore, in most cases, the use of automatic air-break switches and sectionalized power lines should provide an adequate quality of service.

Railroads can also tolerate considerable variations in the supply of voltage without adverse effects. As a general rule, voltage regulation that is acceptable to other customers will be acceptable for railroad loads. In the few instances in which this is not the case, load-tap-changing transformers at the supply substation provide a technical solution.
Rates and Service Arrangements

Service considerations and arrangements for providing power to electrified railroads will be influenced by economic conditions, policies of the railroads and utilities, regulatory and legal considerations, facility costs, contractual requirements, and rate structure and billing considerations. Following are some thoughts and suggestions that may serve as guidelines to assist in developing service agreements.

As a general rule, railroads have a poorer load factor than the average utility customer. This is especially true if each substation is treated as an individual billing or metering point. Unless regulatory approval can be secured to provide special treatment for railroads by considering the impact on the overall system rather than on the individual delivery point, the development of appropriate electric service rates may present significant problems.

Since, unlike the demand of conventional industrial customers, the railroad’s demand point moves with time as the trains move from substation to substation, the development of service arrangements equitable to both the railroad customer and the supplying utility may require a departure from the usual practices and concepts of utility service and pricing.

Costs related to providing the railroad’s power requirements are incurred in four major areas. The railway service tariff must be designed and applied to recover costs in the areas of:

1. Energy (principally fuel and production expenses), including provision for losses to the utility system as a result of single-phase loads;
2. Demand, including some type of minimum demand and careful selection of the billing period (e.g., 15 min, 1 h), as well as consideration of the time and duration of peaks if extensive commuter or passenger operations are involved;
3. Dedicated utility facilities (i.e., charges associated with new utility facilities, such as transmission lines or switchgear required exclusively for service to the electrified railway); and
4. Other utility expenses, which should be covered by a separately stated charge that provides for automatic or periodic adjustments to cover changes in such costs as fuel, labor, materials, services, taxes, and interest (as far as is permitted by applicable utility regulatory agencies and legislation).

Contractual Arrangements

The railroad electrification service contract must be a long-term agreement (20 years or more). The contract should include appropriate cancellation provisions and provision to reduce the power costs if there are improvements in the load factor and power factor. In general, the contract should be comparable to other power service contracts with large industrial customers in order to avoid difficulties in securing regulatory approval.

A major electrification project will usually involve securing electric service from a number of different utilities. Because of franchise and other considerations related to the different service areas (including, in most instances, different regulatory agencies), the cost and details of service will differ among individual utility suppliers. Because of variations in the number of supply points, differences in the financial structures and costs of the utility systems, and differences in railroad load factors and effective railroad load diversity, the separate tariffs negotiated with a single railroad by individual utility suppliers will not, in all probability, be identical in structure or price level. At the same time, it would be desirable for all service agreements to be similar in format and general billing procedures.

A significant obstacle to the establishment of uniform procedures for railroad service by a number of utilities is the possibility that any concerted action taken by several utilities to establish uniform service procedures might raise questions about antitrust activities.

THEORETICAL COST OF SERVICE

The development of a theoretical cost for electric service involves the major components of the service rate and their anticipated typical costs. It must be recognized that actual service costs will be greatly influenced by major variations in construction costs, capital structure, cost of capital, fuel costs, differences between public and investor-owned utilities, allowable rates of return, the rates (under existing industrial tariffs) to which the rail service rate must be compared, system operating costs, and characteristics of the service area and load.

This simplified analysis includes estimated costs for new generating capacity, transmission system, fuel, and other utility costs. The actual cost of generation may be reduced if there are existing facilities to which greater capacity is added; but this varies. Likewise, the allowable rate of return, taxes, and debt-equity ratios may vary from 14 percent to 22 percent or more.

1. Fuel costs (coal-burning plant). If the plant’s power production is 23.3 MWh/kg (10 000 Btu/lb) of coal and its heat rate is 2.75 MJ/MJ (9400 Btu/kW-h) with a transmission system loss of 7 percent and coal costs of $22/Mg ($20/ton), then the fuel costs are 2.78 mils/MJ (10 mils/kW-h).

2. Capital investment carrying charges. Assuming the cost for a coal-burning generating unit for service in 1983 is $550/kW—the Federal Power Commission (1) has estimated $574/kW and Northern States Power Company, in its first quarter 1977 report to its shareholders, estimated $544/kW for units to be placed in service in 1981 to 1983—with an 18 percent carrying charge on the utility investment and a reserve factor of 15 percent as well as an investment in the transmission system of $100/kW with the same 18 percent carrying charge and a 60 percent load factor for the railroad, then the total investment cost is 6.94 mils/MJ (25 mils/kW-h).

3. Administrative and general expenses. Assuming the administrative and general overhead expenses run about 3 percent of the fuel cost of 2.78 mils/MJ and the investment carrying charge of 0.94 mils/MJ, then these expenses amount to 0.28 mils/MJ (1 mil/kW-h).

4. Total cost for delivered power. Adding the fuel cost, the investment carrying charges, and the administrative and general expenses gives a total cost of 10 mils/MJ (36 mils/kW-h) delivered to the railroad substation.

CONCLUSIONS

When limitations with respect to voltage unbalance and single-phase loading are observed, a railroad’s single-phase load can be served without harmful effects to the utility system’s generating or utilization equipment that is currently in service. The provision of a supply of electricity to the mobile loads of a single railroad at a number of different locations, in most cases by several utility companies, poses a number of problems concerning rates, regulatory tariffs, and legal obligations that have not previously been encountered by American utilities.

The electrification of North American railroads re-
The Canadian Railway Electrification Study was commissioned by the Railway Advisory Committee and funded through the Canada Department of Transport's Transportation Development Agency to (a) bring into sharper focus the time frame in which it might be expected that electrification of significant portions of Canadian railways is likely to occur and (b) develop and describe a program of investigation, research, and development designed to permit a smooth transition to effective electrified operation at that time.

It was not intended that the study resolve the question of whether electrification will, or should, take place; the terms of reference required the presumption that it will occur at some future time. However, the study has provided considerable background information that would be necessary to make a decision concerning rail electrification, and it aids in identifying additional studies that would be necessary to such a decision. The study examined a number of factors, including:

1. The future supply and costs of hydrocarbon fuels for railway operations in Canada;
2. A comparison of the technical features of diesel-electric and electric locomotives, including a comparison of capital and operating costs;
3. The future supply and costs of electric energy for railway traction;
4. The technical and cost features of high-voltage overhead catenary;
5. The effects of inductive interference on signaling and communication systems, including a discussion of the nature of the interference and design factors that affect the degree of interference generated;
6. System operating considerations;
7. The requirement for an operational prototype for the Canadian situation;
8. An economic evaluation for a specific, but typical, 650-km (400-mile) segment to determine the importance of numerous factors on both the financial return and the optimum timing for electrification;
9. An examination of rail traffic volume, with projections for the future for main-line track of both the Canadian National Railways and the Canadian Pacific Ltd. and the development of a possible implementation sequence for electrification of roughly 15 300 track km (9500 track miles) over a 30-year period;
10. Identification of some implications of rail electrification;
11. Consideration of the scale and nature of the capital financing required for electrification and its impact on the Canadian economy; and
12. Identification of the additional study necessary to resolve both technical and financial questions and the steps and time required to complete a prototype operating system.

ENERGY SUPPLY AND COST

If the future supply of diesel fuel to the railways could not be guaranteed, then the requirement for electrification of the rail network would become essential. This presumes that the railways continue to be an essential part of Canada's transportation system, that alternative railway fuels (such as hydrogen or coal-derived products) are not available, and that an adequate supply of electric energy is available.

After reviewing statements concerning petroleum supplies in Canada and allocation policies of the federal government, we concluded that Canadian railways will not be crippled by a lack of diesel fuel within the next 50 years. However, on the basis of limited world petroleum supplies, and the projections of crude oil prices, as shown in Figure 1, we must conclude that the relative price of petroleum-based fuels will rise faster than the general inflation rate would suggest. The projected world oil price suggests a price escalation rate 4 percent greater than the general inflation rate. This would lead to the projected diesel fuel costs shown below in terms of 1975 Canadian dollars (1 L = 0.26 gal).

<table>
<thead>
<tr>
<th>Year</th>
<th>Cost ($/L)</th>
</tr>
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<tbody>
<tr>
<td>1980</td>
<td>0.163 to 0.205</td>
</tr>
<tr>
<td>1985</td>
<td>0.198 to 0.249</td>
</tr>
<tr>
<td>1990</td>
<td>0.242 to 0.304</td>
</tr>
<tr>
<td>1995</td>
<td>0.297 to 0.372</td>
</tr>
<tr>
<td>2000</td>
<td>0.361 to 0.464</td>
</tr>
</tbody>
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In Canada, electricity is provided by provincially owned or regulated supply authorities. Each supply authority establishes its own price structure. Naturally, the demand load factor (the average demand divided by the peak demand during, for example, a 30-min period) will significantly affect electric costs. Hencen, to provide a reasonable picture of the comparative costs shown in Table 1, we assumed a 650-km segment of track carrying 18 gross Tg/year (20 million gross tons/year) with substations at 65-km (40-mile) intervals, an energy consumption of 11.7 kW/gross Ggkm (17.1 kW/1000 gross ton-miles), and a power factor of 85 percent. As traffic levels increase, the load factor increases, thereby reducing the unit energy cost.

Rather than using individual substation metering, the possibility of system metering has been considered. This would involve connecting individual substations to a railway-owned distribution line from a single supply authority. Significant improvement in the load factor is possible, accompanied by a consequent reduction in the unit energy cost, as shown in Table 1.

REFERENCE